ELECTRIC-FIELD ACTUATED CHROMOGENIC MATERIALS BASED ON MOLECULES WITH A ROTATING MIDDLE SEGMENT FOR APPLICATIONS IN PHOTONIC SWITCHING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a continuation-in-part application of Serial No. 09/844,862, filed April 27, 2001, which in turn is a continuation-in-part application of Serial No. 09/823,195, filed March 29, 2001, which in turn is a continuation-in-part application of Serial No. 09/759,438, filed January 12, 2001, which in turn is a continuation-in-part application of Serial No. 09/738,793, filed December 14, 2000.

[0002] The present application is also a continuation-in-part application of Serial No. 09/846,135, filed April 30, 2001, which in turn is a continuation-in-part application of Serial No. 09/823,195, filed March 29, 2001, which in turn is a continuation-in-part application of Serial No. 09/759,438, filed January 12, 2001, which in turn is a continuation-in-part application of Serial No. 09/738,793, filed December 14, 2000.

[0003] The present application is an improvement over the foregoing applications in that it is directed to classes of molecules that provide switching from one state to a different state, characterized by a change in the optical properties, including color, of the molecules. In the case of color switching, the present invention turns ink or dye molecules into active opto-electronic devices that can be switched with an external electric field.

[0004] The present application is related to application Serial No. 09/759,438, filed January 12, 2001, which is directed to bistable molecular mechanical devices with an appended rotor activated by an electric field for electronic switching, gating, and memory applications. The class of molecules disclosed in that application have been found to be useful in the optical switching devices of the present application.

TECHNICAL FIELD

[0005] The present invention relates generally to optical devices whose functional length scales are measured in nanometers, and, more particularly, to classes of molecules that provide optical switching. Optical devices both of micrometer and nanometer scale may be constructed in accordance with the teachings herein.

BACKGROUND ART

[0006] The area of molecular electronics is in its infancy. To date, there have been two convincing demonstrations of molecules as electronic switches published in the technical literature; see, C.P. Collier et al., Science, Vol. 285, pp. 391-394 (16 July 1999) and C.P. Collier et al., Science, Vol. 289, pp. 1172-1175 (18 August 2000), but there is a great deal of speculation and interest within the scientific community surrounding this topic. In the published work, a molecule called a rotaxane or a catenane was trapped between two metal electrodes and caused to switch from an ON state to an OFF state by the application of a positive bias across the molecule. The ON and OFF states differed in resistivity by about a factor of 100 and 5, respectively, for the rotaxane and catenane.

[0007] The primary problem with the rotaxane was that it is an irreversible switch. It can only be toggled once. Thus, it can be used in a programmable read-only memory (PROM), but not in a RAM-like (random access memory) device nor in a reconfigurable system, such as a defect-tolerant communications

and logic network. In addition, the rotaxane requires an oxidation and/or reduction reaction to occur before the switch can be toggled. This requires the expenditure of a significant amount of energy to toggle the switch. In addition, the large and complex nature of rotaxanes and related compounds potentially makes the switching times of the molecules slow. The primary problems with the catenanes are small ON-to-OFF ratio and a slow switching time.

[0008] Currently, there are a wide variety of known chromogenic materials that can provide optical switching in thin film form. These materials and their applications have been reviewed recently by C.B. Greenberg, Thin Solid Films, Vol. 251, pp. 81-93 (1994); R.J. Mortimer, Chemical Society Reviews, Vol. 26, pp. 147-156 (1997); and S.A. Agnihotry, Bulletin of Electrochemistry, Vol. 12, pp. 707-712 (1996). These materials are currently being studied for several applications, including active darkening of sunglasses, active darkening of windows for intelligent light and thermal management of buildings, and various types of optical displays, such as heads-up displays on the inside of windshields of automobiles or airplanes and eyeglass displays.

[0009] Despite their long history of great promise, there are very few photon gating devices made from the existing classes of electrochromic materials. This is because most of them require an oxidation-reduction reaction that involves the transport of ions, such as H^+, Li^+, or Na^+ through some type of liquid or solid electrolyte. Finding the appropriate electrolyte is a major problem, as is the slow speed of any device that requires transport of ions. Furthermore, such reactions are extremely sensitive to background contamination, such as oxygen or other species, and thus degradation of the chromogenic electrodes is a major limitation.

[0010] In fact, for photonic switching applications such as a crossbar switch router for a fiber optic communications network, the lack of a suitable chromogenic material has forced companies to use very different approaches: (a) transform the optical signal into an electronic signal, perform the switching operation, and then transform back to an optical signal before launching into a fiber (this is the most frequent solution used today, but it is very inefficient and the electronics have a hard time keeping up with the data rates of the optical

system); (b) use a moving-mirror array made by micro-electromechanical (MEM) processing to switch optical data packets (this has the disadvantage that extremely high tolerances are required for the device, which makes it very expensive); and (c) using ink jet technology to push bubbles into a chamber to create a mirror to deflect an optical beam (this approach again requires precision manufacturing and the switching time is slow).

[0011] Thus, what is needed is a molecular system that avoids chemical oxidation and/or reduction, permits reasonably rapid switching from a first state to a second, and can be used in a variety of optical devices.

DISCLOSURE OF INVENTION

[0012] In accordance with embodiments disclosed herein, a molecular system is provided for optical switching. The molecular system has an electric field induced band gap change that occurs via a molecular conformation change or an isomerization. Changing of extended conjugation via chemical bonding change to change the band gap is accomplished by providing the molecular system with one rotating portion (rotor) and two stationary portions (stators), between which the rotor is attached.

[0013] The embodiments disclosed herein are suitably employed in the fabrication of, for example, optical switches that can be assembled easily to make displays, electronic books, rewrittable media, electronic lenses, electrically-controlled tinting for windows and mirrors, optical crossbar switches for fiber optic communications, and more. Such applications are discussed elsewhere, and are not germane to the present invention, except to the extent that the optical switch of the present invention is employed in the construction of apparatus of such applications.

[0014] The bistable molecules evidence high switching speed. Such molecules are essentially stable against switching due to thermal fluctuations. These molecules are useful for optical switches, in which the molecules change color when changing state. This property can be used for a wide variety of dis-

play devices or any other application enabled by a material that can change color or transform from transparent to colored.

[0015] Thus, the molecule is not oxidized nor reduced in the toggling of the switch. Also, the part of the molecule that moves is quite small, so the switching time should be very fast. Also, the molecules are much simpler and thus easier and cheaper to make than the rotaxanes, catenanes, and related compounds.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a schematic representation (perspective, transparent view) of a two color (e.g., black and white) display screen construction for use in accordance with the present invention;

[0017] FIG. 1a is a detail for a colorant layer element of the display screen depicted in FIG. 1;

[0018] FIG. 2 is a schematic representation (perspective, transparent view) of a full-color display screen construction for use in accordance with the present invention;

[0019] FIG. 3 is a schematic representation of a scan addressing embodiment of a two-color display screen construction for use in accordance with the present invention; and

[0020] FIG. 4 is a schematic model depicting an E-field-induced band gap change via molecular conformation change (rotor/stator type of model).

BEST MODES FOR CARRYING OUT THE INVENTION

<u>Definitions</u>

[0021] The term “self-assembled” as used herein refers to a system that naturally adopts some geometric pattern because of the identity of the components of the system; the system achieves at least a local minimum in its energy by adopting this configuration.

[0022] The term “singly configurable” means that a switch can change its state only once via an irreversible process such as an oxidation or reduction reaction; such a switch can be the basis of a programmable read-only memory (PROM), for example.

[0023] The term “reconfigurable” means that a switch can change its state multiple times via a reversible process such as an oxidation or reduction; in other words, the switch can be opened and closed multiple times, such as the memory bits in a random access memory (RAM) or a color pixel in a display.

[0024] The term “bi-stable” as applied to a molecule means a molecule having two relatively low energy states separated by an energy (or activation) barrier. The molecule may be either irreversibly switched from one state to the other (singly configurable) or reversibly switched from one state to the other (reconfigurable).

[0025] Micron-scale dimensions refers to dimensions that range from 1 micrometer to a few micrometers in size.

[0026] Sub-micron scale dimensions refers to dimensions that range from 1 micrometer down to 0.05 micrometers.

[0027] Nanometer scale dimensions refers to dimensions that range from 0.1 nanometers to 50 nanometers (0.05 micrometers).

[0028] Micron-scale and submicron-scale wires refers to rod or ribbon-shaped conductors or semiconductors with widths or diameters having the dimensions of 0.05 to 10 micrometers, heights that can range from a few tens of nanometers to a micrometer, and lengths of several micrometers and longer.

[0029] “HOMO” is the common chemical acronym for “highest occupied molecular orbital”, while “LUMO” is the common chemical acronym for “lowest unoccupied molecular orbital”. HOMOs and LUMOs are responsible for electronic conduction in molecules and the energy difference between the HOMO and LUMO and other energetically nearby molecular orbitals is responsible for the color of the molecule.

[0030] An optical switch, in the context of the present invention, involves changes in the electro-magnetic properties of the molecules, both within and outside that detectable by the human eye, e.g., ranging from the far infra-red

(IR) to deep ultraviolet UV). Optical switching includes changes in properties such as absorption, reflection, refraction, diffraction, and diffuse scattering of electro-magnetic radiation.

[0031] The term “transparency” is defined within the visible spectrum to mean that optically, light passing through the colorant is not impeded or altered except in the region in which the colorant spectrally absorbs. For example, if the molecular colorant does not absorb in the visible spectrum, then the colorant will appear to have water clear transparency.

[0032] The term “omni-ambient illumination viewability” is defined herein as the viewability under any ambient illumination condition to which the eye is responsive.

<u>Optical Switches</u>

[0033] Optical switches are described in greater detail in co-pending U.S. application Serial No. _______, filed on ______ [PD-10005747-1]. A generic example taken from that application is depicted herein in FIG. 1, wherein a display screen 100 is shown that incorporates at least one colorant layer 101. The colorant layer 101 comprises a pixel array using electrical field switchable, reconfigurable, dye or pigment molecules of the present invention, described in greater detail below and generically referred to as a “molecular colorant”. Each dye or pigment molecule is field switchable either between an image color (e.g., black) and transparent or between two different colors (e.g., red and green).

[0034] Referring briefly to FIG. 1a, the colorant layer 101 is an addressable pixel array formed of bi-stable molecules arrayed such that a selected set of molecules correlates to one pixel. The colorant layer 101 is a thin layer coated on a background substrate 103 having the display's intended background color (e.g., white). The substrate 103 may comprise, for example, a high dielectric pigment (e.g., titania) in a polymer binder that provides good white color and opacity while also minimizing the voltage drop across the layer. The stratified combination of colorant layer 101 and substrate 103 thus is fully analogous to a layer of ink on paper. In a blank mode, or erased state, each molecule is switched to its transparent orientation; the “layer of ink” is invisible.

The background (e.g., white pixels) shows through in those pixel areas where the colorant layer 101 molecules are switched to the transparent orientation. A transparent view-through layer 105, such as of a clear plastic or glass, is provided superjacent to the colorant-background sandwich to provide appropriate protection. The view-through layer 105 has a transparent electrode array 107 for pixel column or row activation mounted thereto and positioned superjacently to the colorant layer 101. The background substrate 103 has a complementary electrode array 109 for pixel row or column activation mounted thereto (it will be recognized by those skilled in the art that a specific implementation of the stratification of the electrode arrays 107, 109 for matrix addressing and field writing of the individual pixels may vary in accordance with conventional electrical engineering practices). Optionally, the pixels are sandwiched by employing thin film transistor (TFT) driver technology as would be known in the art.

[0035] The present display 100 is capable of the same contrast and color as hard copy print. A molecular colorant is ideal because its size and mass are infinitesimally small, allowing resolution and colorant switching times that are limited only by the field writing electrodes and circuitry. Like ink, the colorant layer 101 may develop adequate density in a sub-micron to micron thin layer, potentially lowering the field voltage required to switch the colorant between logic states and thus allowing the use of inexpensive drive circuitry.

[0036] Suitable reconfigurable bi-stable molecules for use in such displays are disclosed below and claimed herein. In the main, these molecules have optical properties (e.g., color) that are determined by the extent of their π orbital electron conjugation. The optical properties, including color or transparency, of the molecule change with field polarity applied across the molecule and remains chromatically stable in the absence of an applied electric field. By disrupting the continuity of conjugation across a molecule, the molecule may be changed from one optical state to another, e.g., colored to transparent. Electric dipoles may be designed into the colorant that can physically cause this disruption by rotating or otherwise distorting certain segments of the dye or pigment molecule relative to other segments, when an external electric field is applied or changed.

[0037] The colorant layer 101 is a homogeneous layer of molecules which are preferably colored (e.g., black, cyan, magenta, or yellow) in a more-conjugated orientation and transparent in a less-conjugated orientation. By making the abutting background substrate 103 white, the colorant layer 101 may thereby produce high contrast black and white, and colored images. The colorant layer 101 may comprise a single field switchable dye or pigment or may comprise a mixture of different switchable dyes or pigments that collectively produce a composite color (e.g., black). By using a molecular colorant, the resolution of the produced image is limited only by the electric field resolution produced by the electrode array 107, 109. The molecular colorant additionally has virtually instantaneous switching speed, beneficial to the needs of fast scanning (as described with respect to FIG. 3 hereinafter). In certain cases, the molecular colorant may be contained in a polymeric layer. Polymers for producing such coatings are well-known, and include, for example, acrylates, urethanes, and the like. Alternatively, the colorant layer 101 may be self-assembled.

[0038] In one embodiment, the colorant layer 101 is offered as a substitute for matrix-addressed liquid crystal flat panel displays. As is well-known for such displays, each pixel is addressed through rows and columns of fixed-position electrode arrays, e.g., 107, 109. The fixed-position electrode arrays 107, 109 consist of conventional crossbar electrodes 111, 113 that sandwich the colorant layer 101 to form an overlapping grid (matrix) of pixels, each pixel being addressed at the point of electrode overlap. The crossbar electrodes 111, 113 comprise parallel, spaced electrode lines arranged in electrode rows and columns, where the row and column electrodes are separated on opposing sides of the colorant layer 101. Preferably, a first set of transparent crossbar electrodes 107 (201, 203 in FIG. 2 described in detail hereinafter) is formed by thin film deposition of indium tin oxide (ITO) on a transparent substrate (e.g., glass). These row addressable pixel crossbar electrodes 107 are formed in the ITO layer using conventional thin film patterning and etching techniques. The colorant layer 101 and background substrate 103 are sequentially coated over or mounted to the transparent electrode layer, using conventional thin film techniques (e.g., vapor deposition) or thick film techniques (e.g., silkscreen, spin

cast, or the like). Additional coating techniques include Langmuir-Blodgett deposition and self-assembled monolayers. Column addressable pixel crossbar electrodes 109 (202, 204 in FIG. 2) are preferably constructed in like manner to the row electrodes 107. The column addressable pixel crossbar electrodes 109 may optionally be constructed on a separate substrate that is subsequently adhered to the white coating using conventional techniques.

[0039] This display 100, 200 provides print-on-paper-like contrast, color, viewing angle, and omni-ambient illumination viewability by elimination of the polarization layers required for known liquid crystal colorants. Using the described-display also allows a significant reduction in power drain. Whereas liquid crystals require a holding field even for a static image, the present molecules of the colorant layer 101 can be modal in the absence of a field when bi-stable molecules are used. Thus, the present bi-stable colorant layer 101 only requires a field when a pixel is changed and only for that pixel. The power and image quality improvements will provide significant benefit in battery life and display readability, under a wider range of viewing and illumination conditions for appliances (e.g., wristwatches, calculators, cell phones, or other mobile electronic applications) television monitors and computer displays. Furthermore, the colorant layer may comprise a mosaic of colored pixels using an array of bi-stable color molecules of various colors for lower resolution color displays.

[0040] Since each colorant molecule in colorant layer 101 is transparent outside of the colorant absorption band, then multiple colorant layers may be superimposed and separately addressed to produce higher resolution color displays than currently available. FIG. 2 is a schematic illustration of this second embodiment. A high resolution, full color, matrix addressable, display screen 200 comprises alternating layers of transparent electrodes - row electrodes 201, 203 and column electrodes 202 and 204 - and a plurality of colorant layers 205, 207, 209, each having a different color molecule array. Since each pixel in each colorant layer may be colored or transparent, the color of a given pixel may be made from any one or a combination of the color layers (e.g., cyan, magenta, yellow, black) at the full address resolution of the display. When all colorant layers 205, 207, 209 for a pixel are made transparent, then the pixel shows the

background substrate 103 (e.g., white). Such a display offers the benefit of three or more times resolution over present matrix LCD devices having the same pixel density but that rely on single layer mosaic color. Details of the fabrication of the display are set forth in the above-mentioned co-pending application.

[0041] The color to be set for each pixel is addressed by applying a voltage across the electrodes directly adjacent to the selected color layer. For example, assuming yellow is the uppermost colorant layer 205, magenta is the next colorant layer 207, and cyan is the third colorant layer 209, then pixels in the yellow layer are addressed through row electrodes 201 and column electrodes 202, magenta through column electrodes 202 and row electrodes 203, and cyan through row electrodes 203 and column electrodes 204. This simple common electrode addressing scheme is made possible because each colorant molecule is color stable in the absence of an applied electric field.

[0042] FIG. 3 depicts a third embodiment, which employs scan-addressing rather than matrix-addressing. Matrix address displays are presently limited in resolution by the number of address lines and spaces that may be patterned over the relatively large two-dimensional surface of a display, each line connecting pixel row or column to the outer edge of the display area. In this third embodiment, the bi-stable molecular colorant layer 101 and background substrate 103 layer construction is combined with a scanning electrode array printhead to provide a scanning electrode display apparatus 300 having the same readability benefits as the first two embodiments described above, with the addition of commercial publishing resolution. Scanning electrode arrays and drive electronics are common to electrostatic printers and their constructions and interfaces are well-known. Basically, remembering that the bi-stable molecular switch does not require a holding field, the scanning electrode array display apparatus 300 changes a displayed image by printing a pixel row at a time. The scanning electrode array display apparatus 300 thus provides far greater resolution by virtue of the ability to alternate odd and even electrode address lines along opposing sides of the array, to include multiple address layers with pass-through array connections and to stagger multiple arrays that proportion-

ately superimpose during a scan. The colorant layer 101 may again be patterned with a color mosaic to produce an exceptionally high resolution scanning color display.

[0043] More specifically, the third embodiment as shown in FIG. 3 comprises a display screen 302, a scanned electrode array 304, and array translation mechanism 301 to accurately move the electrode array across the surface of the screen. The display screen 302 again comprises a background substrate 103, a transparent view-through layer 105, and at least one bi-stable molecule colorant layer 101. The colorant layer 101 may include a homogeneous monochrome colorant (e.g., black) or color mosaic, as described herein above. The scanned electrode array 304 comprises a linear array or equivalent staggered array of electrodes in contact or near contact with the background substrate 103. A staggered array of electrodes may be used, for example, to minimize field crosstalk between otherwise adjacent electrodes and to increase display resolution.

[0044] In operation, each electrode is sized, positioned, and electrically addressed to provide an appropriate electric field, represented by the arrow labeled "E", across the colorant layer 101 at a given pixel location along a pixel column. The field E may be oriented perpendicular to the plane of the colorant layer 101 or parallel to it, depending on the color switching axis of the colorant molecules. A perpendicular field may be produced by placing a common electrode (e.g., an ITO layer) on the opposing coating side to the electrode array. The electrode array may also be constructed to emit fringe fields; a parallel fringe field may be produced by placing a common electrode adjacent and parallel to the array. A perpendicular fringe field may be produced by placing symmetrically spaced parallel common electrodes about the electrode array(s). The voltage is adjusted so that the dominant field line formed directly beneath the array 304 is sufficiently strong to switch the addressed colorant molecule(s) and divided return lines are not. Additional information regarding alternate embodiments and scanning mechanisms are discussed in the above-mentioned copending application.

Present Embodiments

[0045] In accordance with the embodiments disclosed herein, molecules evidencing switching of a rotor portion with respect to two stator portions is provided for the colorant layer 101. The general idea is to design into the molecules a rotatable middle segment (rotor) that has a large dipole moment (see Examples 1 and 2, below) and that links two other portions of the molecule that are immobilized (stators). Under the influence of an applied electric field, the vector dipole moment of the rotor will attempt to align parallel to the direction of the external field. However, the molecule is designed such that there are inter- and/or intra-molecular forces, such as hydrogen bonding or dipole-dipole interactions as well as steric repulsions, which stabilize the rotor in particular orientations with respect to the stators. Thus, a large field is required to cause the rotor to unlatch from its initial orientation and rotate with respect to the stators, if the direction of the applied field is opposite to that of the dipole of the rotor. Once switched into a particular orientation, the molecule will remain in that orientation until it is switched out. However, a key component of the molecule design is that there is a steric repulsion that will prevent the rotor from rotating through a complete 180 degree half cycle. Instead, the rotation is halted by the steric interaction of bulky groups on the rotor and stators at an angle of approximately 90 degrees from the initial orientation. Furthermore, this 90 degree orientation is stabilized by a different set of inter- and/or intramolecular hydrogen bonds or dipole interactions, and is thus latched into place even after the applied field is turned off. For switch molecules, this ability to latch the rotor between two states separated by approximately 90 degrees from the stators is crucial.

[0046] In the ideal case, for the orientation where the rotor and stators are all co-planar, the molecule is completely conjugated. Thus, the p,π-electrons of the molecule, through its highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), are delocalized over the entire molecule (optical state I). In the case where the rotor is rotated by 90 degrees with respect to the stators, the conjugation of the molecule is broken and the HOMO and LUMO are no longer delocalized over the entire molecule (optical

state II). Thus, the molecule is reversibly switchable between the two optical states.

[0047] The following requirements must be met in this stator-rotor-stator model:

[0048] (a) The molecule must have one rotor and two stator segments;

[0049] (b) In one state of the molecule, there should be delocalized HOMOs and/or LUMOs (π-states and/or non-bonding orbitals) that extend over a large portion of the entire molecule (rotor and stators), whereas in the other state, the orbitals are localized on the rotor and stators;

[0050] (c) The connecting unit between rotor and each stator can be a single σ-bond or at least one atom with (1) non-bonding electrons (p or other electrons), or (2) π-electrons, or (3) π-electrons and non-bonding electron(s);

[0051] (d) The non-bonding electrons, or π-electrons, or π-electrons and non-bonding electron(s) of the rotor and stators can be localized or de-localized depending on the conformation of the molecule, while the rotor rotates when activated by an E-field;

[0052] (e) The conformation(s) of the molecule can be E-field dependent or bi-stable;

[0053] (f) The bi-stable state(s) can be achieved by intra- or inter-molecular forces such as hydrogen bonding, Coulomb force, van der Waals force, metal ion complex or dipole inter-stabilization; and

[0054] (g) The band gap of the molecule will change depending on the degree of non-bonding electron, or π-electron, or π-electron and non-bonding electron de-localization of the molecule. This will control the optical properties (e.g., color and/or index of refraction, etc.) of the molecule.

[0055] Following are two examples of this model (Examples 1 and 2):

[0056] The novel bi-modal molecules disclosed herein are active optical devices that can be switched with an external electric field. Preferably, the colorant molecules are bi-stable. The general idea is to design into the molecules a rotatable middle segment (rotor) 432 that has a large dipole moment (see Ex-

amples 1 and 2) and that links two other portions of the molecule 430 that are immobilized (stators) 434, as illustrated in FIG. 4. Under the influence of an applied electric field, the vector dipole moment of the rotor 432 will attempt to align parallel to the direction of the external field. However, the molecule 430 is designed such that there are inter- and/or intra-molecular forces, such as hydrogen bonding or dipole-dipole interactions as well as steric repulsions, that stabilize the rotor 432 in particular orientations with respect to the stators 434. Thus, a large electric field is required to cause the rotor 432 to unlatch from its initial orientation and rotate with respect to the stators 434.

[0057] Once switched into a particular orientation, the molecule 430 will remain in that orientation until it is switched to a different orientation, or reconfigured. However, a key component of the molecule design is that there is a steric repulsion or hindrance that will prevent the rotor 432 from rotating through a complete 180 degree half cycle. Instead, the rotation is halted by the steric interaction of bulky groups on the rotor 432 and stators 434 at an electrically significant angle of typically between 10° and 170° from the initial orientation. For the purposes of illustration, this angle is shown as 90° in the present application. Furthermore, this switching orientation may be stabilized by a different set of inter- and/or intra-molecular hydrogen bonds or dipole interactions, and is thus latched in place even after the applied field is turned off. For bi-stable switch molecules, this ability to latch the rotor 432 between two states separated by an electrically significant rotation from the stators is crucial.

[0058] The foregoing strategy may be generalized to design colorant molecules to provide several switching steps so as to allow multiple states (more than two) to produce a multi-state (e.g., multi-color) system. Such molecules permit the optical properties of the colorant layer to be tuned continuously with a decreasing or increasing electric field, or changed abruptly from one state to another by applying a pulsed field.

[0059] Further, the colorant molecules may be designed to include the case of no, or low, activation barrier for fast but volatile switching. In this latter situation, bi-stability is not required, and the molecule is switched into one state by the electric field and relaxes back into its original state upon removal of the field

("bi-modal"). In effect, these forms of the bi-modal colorant molecules are "self-erasing". In contrast, with bi-stable colorant molecules, the colorant molecule remains latched in its state upon removal of the field (non-volatile switch), and the presence of the activation barrier in that case requires application of an opposite field to switch the molecule back to its previous state.

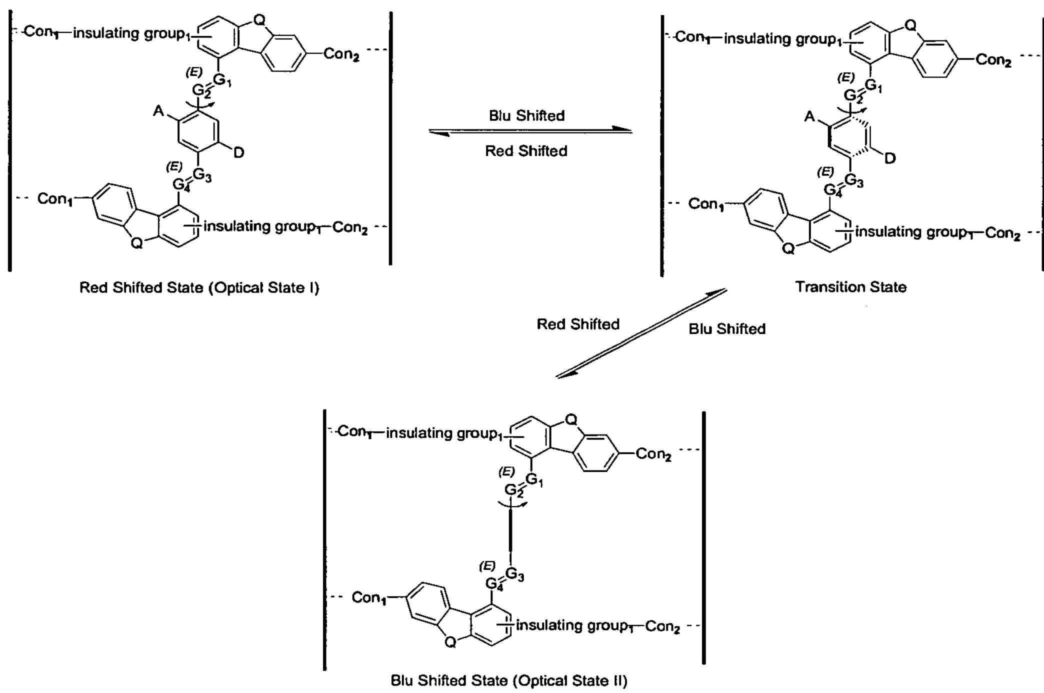
[0060] When the rotor 432 and stators 434 are all co-planar, the molecule is referred to as "more-conjugated". Thus, the non-bonding electrons, or π-electrons, or π-electrons and non-bonding electrons of the molecule, through its highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO), are delocalized over a large portion of the molecule 430. This is referred to as a "red-shifted" for the molecule, or "optical state I". In the case where the rotor 432 is rotated out of conjugation by approximately 10° to 170° with respect to the stators 434, the conjugation of the molecule 430 is broken and the HOMO and LUMO are localized over smaller portions of the molecule, referred to as "less-conjugated". This is a "blue-shifted state" of the molecule 430, or "optical state II". Thus, the molecule 430 is reversibly switchable between two different optical states.

[0061] It will be appreciated by those skilled in the art that in the ideal case, when the rotor 432 and stators 434 are completely coplanar, then the molecule is fully conjugated, and when the rotor 432 is rotated at an angle of 90° with respect to the stators 434, then the molecule is non-conjugated. However, due to thermal fluctuations, these ideal states are not fully realized, and the molecule is thus referred to as being "more-conjugated" in the former case and "less-conjugated" in the latter case. Further, the terms "red-shifted" and "blue-shifted" are not meant to convey any relationship to hue, but rather the direction in the electromagnetic energy spectrum of the energy shift of the gap between the HOMO and LUMO states.

[0062] Examples 1 and 2 show two different orientations for switching the molecules. In Example 1, the rotation axis of the rotor is designed to be nearly perpendicular to the net current-carrying axis of the molecules, whereas in Example 2, the rotation axis is parallel to the orientation axis of the molecule. These designs allow different geometries of molecular films and electrodes to

be used, depending on the desired results. Both generic and real molecular structures are presented for each example. Examples 1a and 2a are generic molecular structures to show two different orientations for switching the molecules, and Examples 1b and 2b are two real molecular structures.

[0063] Turning first to Example 1, this depicts a first embodiment of the bi-stable molecular mechanical device of the present invention. Example 1a below depicts a generic molecular implementation for the stator-rotor-stator model.



Example 1a

[0064] where:

[0065] The letter A represents an Acceptor group; it is an electron-withdrawing group. It may be one of following: hydrogen, carboxylic acid or its derivatives, sulfuric acid or its derivatives, phosphoric acid or its derivatives, nitro, nitrile, hetero atoms (e.g., N, O, S, P, F, Cl, Br), or functional group with at least one of above-mentioned hetero atoms (e.g., OH, SH, NH, etc.), hydrocarbon (either saturated or unsaturated) or substituted hydrocarbon.

[0066] The letter D represents a Donor group; it is an electron-donating group. It may be one of following: hydrogen, amine, OH, SH, ether, hydrocarbon (either saturated or unsaturated), or substituted hydrocarbon or functional group with at least one of hetero atom (e.g., B, Si, N, O, S, P, I). The donor is differentiated from the acceptor by that fact that it is relatively less electronegative, or more electropositive, than the acceptor group on the molecule.

[0067] The letters Con_1 and Con_2 represent connecting units between one molecule and another molecule or between a molecule and the solid substrate e.g., metal electrode, inorganic substrate, or organic substrate). They may be one of the following: hydrogen (utilizing a hydrogen bond), multivalent hetero atoms (i.e., C, N, O, S, P, etc.) or functional groups containing the hetero atoms (e.g., NH, PH, etc.), hydrocarbons (saturated or unsaturated), or substituted hydrocarbons.

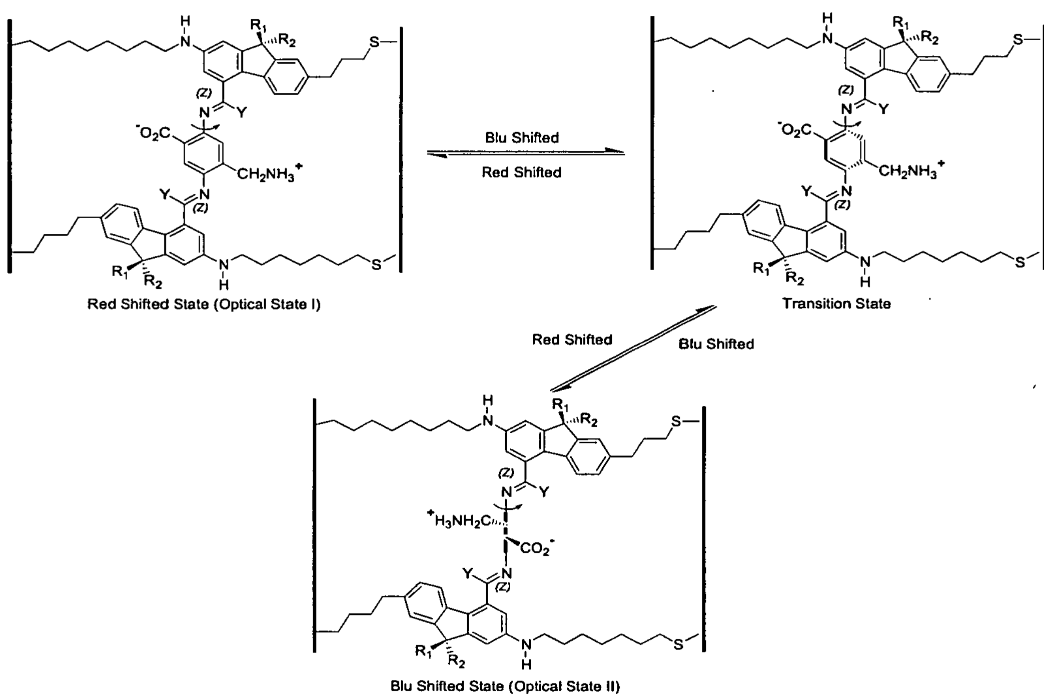
[0068] The letters G_1, G_2, G_3, and G_4 are bridging groups. The function of these bridging groups is to connect the stator and rotor or to connect two or more conjugated rings to achieve a desired electronic property. They may be any one of the following: hetero atoms (e.g., N, O, S, P, etc.) or functional groups with at least one of above-mentioned hetero atoms (e.g., NH or NHNH, etc.), hydrocarbons (either saturated or unsaturated) or substituted hydrocarbons. The connector may alternately comprise a single atom bridge such as an ether bridge with an oxygen atom, or a direct sigma bond between the rotor and stator.

[0069] The letter Q is used here to designate a connecting unit between two phenyl rings. It can be any one of following: S, O, NH, NR, hydrocarbon, or substituted hydrocarbon.

[0070] The word "blue" is contracted to "blu" for simplicity in this and in the remaining diagrams.

[0071] In Example 1a above, the vertical thick lines represent other molecules or solid substrates. The direction of the switching field is perpendicular to the vertical dotted lines. Such a configuration is employed for electrical switching; for optical switching, the linking moieties may be eliminated, and the molecule may be simply placed between the two electrodes. They may also be simply used to link one molecule to another molecule or a molecule to an organic or inorganic substrate.

[0072] Example 1b below is a real molecular example of the stator-rotor-stator model mentioned above:



Example 1b

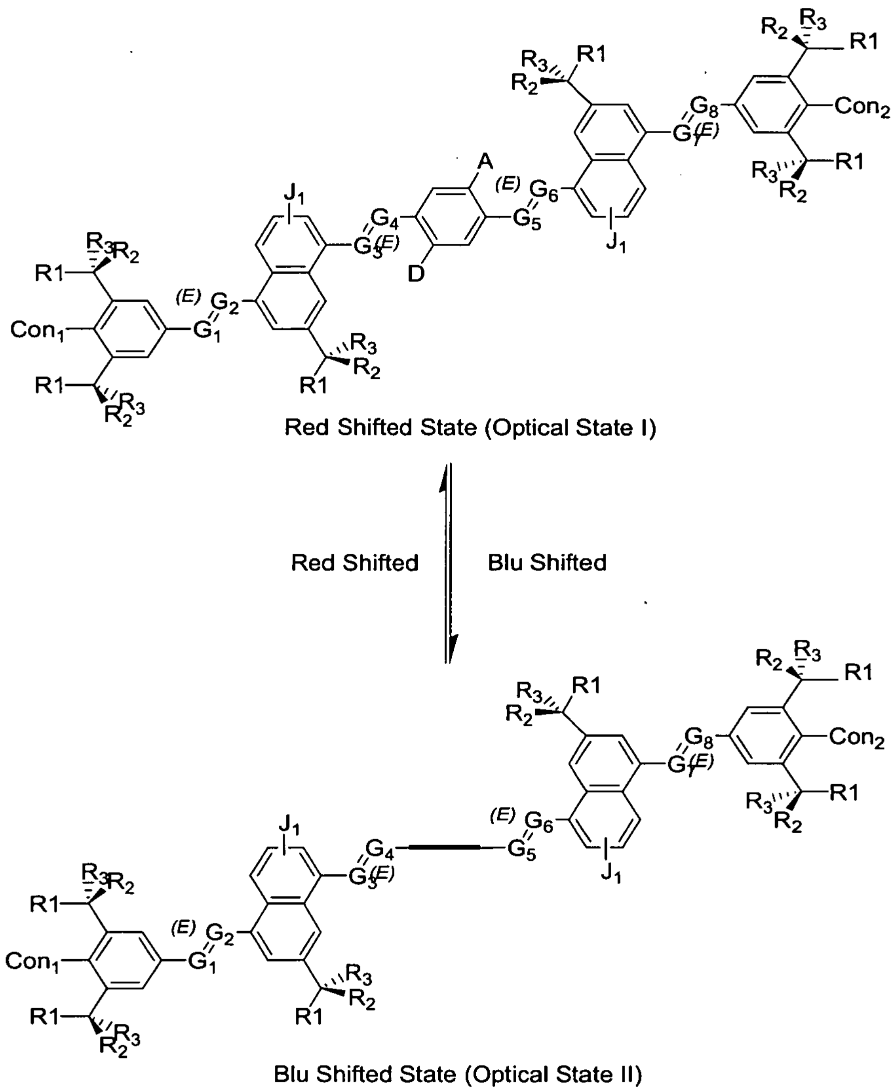
[0073] The molecule shown above (Example 1b) has been designed with the internal rotor 432 perpendicular to the orientation or current-flow axis of the entire molecule 430. In this case, the external field is applied along the orientation axis of the molecule 430 as pictured - the electrodes (vertical thick lines) are oriented perpendicular to the plane of the paper and perpendicular to the orien-

tation axis of the molecule 430. Application of an electric field oriented from left to right in the diagrams will cause the rotor 432 as pictured in the upper left diagram to rotate to the position shown on the lower diagram, and vice versa. In this case, the rotor 432 as pictured in the lower diagram is not coplanar with the rest of the molecule, so this is the blue-shifted optical state of the molecule, whereas the rotor is substantially coplanar with the rest of the molecule on the upper left diagram, so this is the red-shifted optical state of the molecule. The structure shown in the upper right diagram depicts the transition state of rotation between the upper left diagram (co-planar, conjugated) and the lower diagram (central portion rotated, non-conjugated).

[0074] The molecule depicted in Example 1b is chromatically transparent or blue-shifted in the non-conjugated state. In the conjugated state, the molecule is colored or is red-shifted.

[0075] For molecules of the type shown in Example 1, a single monolayer molecular film is grown, for example using Langmuir-Blodgett techniques or self-assembled monolayers, such that the orientation axis of the molecules is perpendicular to the plane of the electrodes used to switch the molecules. Electrodes may be deposited in the manner described by Collier et al, <u>supra</u>, or methods described in the above-referenced patent applications and issued patent. Alternate thicker film deposition techniques include vapor phase deposition, contact or ink-jet printing, or silk screening.

[0076] Turning now to Example 2, this depicts a second embodiment of the bi-stable molecular mechanical device of the present invention. Example 2a below depicts a second generic molecular example for stator-rotor-stator configuration of the present invention.



Example 2a

[0077] where:

[0078] The letter A represents an Acceptor group; it is an electron-withdrawing group. It may be one of following: hydrogen, carboxylic acid or its derivatives, sulfuric acid or its derivatives, phosphoric acid or its derivatives, nitro, nitrile, hetero atoms (e.g., N, O, S, P, F, Cl, Br), or functional group with at least one of

above-mentioned hetero atoms (e.g., OH, SH, NH, etc.), hydrocarbon (either saturated or unsaturated) or substituted hydrocarbon.

[0079] The letter D represents a Donor group; it is an electron-donating group. It may be one of following: hydrogen, amine, OH, SH, ether, hydrocarbon (either saturated or unsaturated), or substituted hydrocarbon or functional group with at least one of hetero atom (e.g., B, Si, I, N, O, S, P). The donor is differentiated from the acceptor by that fact that it is relatively less electronegative, or more electropositive, than the acceptor group on the molecule.

[0080] The letters Con_1 and Con_2 represent connecting units between one molecule and another molecule or between a molecule and the solid substrate e.g., metal electrode, inorganic substrate, or organic substrate). They may be one of the following: hydrogen (utilizing a hydrogen bond), multivalent hetero atoms (i.e., C, N, O, S, P, etc.) or functional groups containing the hetero atoms (e.g., NH, PH, etc.), hydrocarbons (saturated or unsaturated), or substituted hydrocarbons.

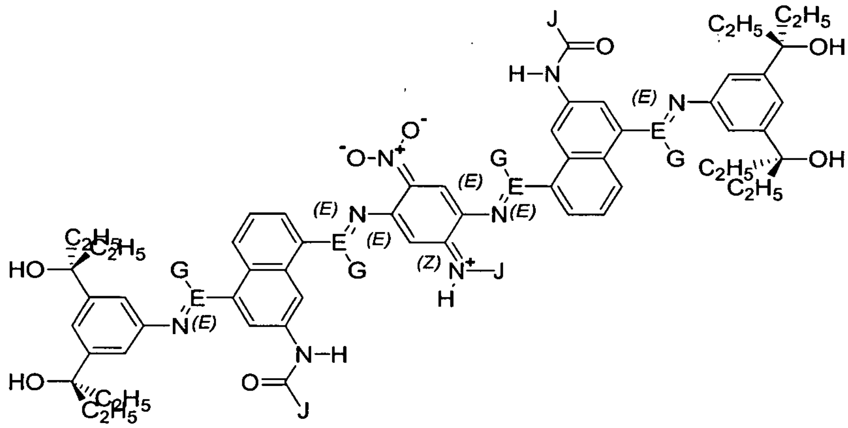
[0081] The letters R_1, R_2 and R_3 represent spacing groups built into the molecule. The function of these spacer units is to provide an appropriate 3-dimensional scaffolding to allow the molecules to pack together while providing rotational space for each rotor. They may be any one of the following: hydrogen, hydrocarbon (either saturated or unsaturated) or substituted hydrocarbon.

[0082] The letters G_1, G_2, G_3, G_4, G_5, G_6, G_7, and G_8 are bridging groups. The function of these bridging groups is to connect the stator and rotor or to connect two or more conjugated rings to achieve a desired electronic property. They may be any one of the following: hetero atoms (e.g., C, N, O, S, P, etc.) or functional group with at least one of above-mentioned hetero atoms (e.g., NH or NHNH, etc.), hydrocarbons (either saturated or unsaturated) or substituted hydrocarbons. The connector may alternately comprise a single atom bridge such as an ether bridge with an oxygen atom, or a direct sigma bond between the rotor and stator.

[0083] The letters J_1 and J_2 represent tuning groups built into the molecule. The function of these tuning groups (e.g., OH, NHR, COOH, CN, nitro, etc.) is to provide an appropriate functional effect (e.g. both inductive effect and resonance ef-

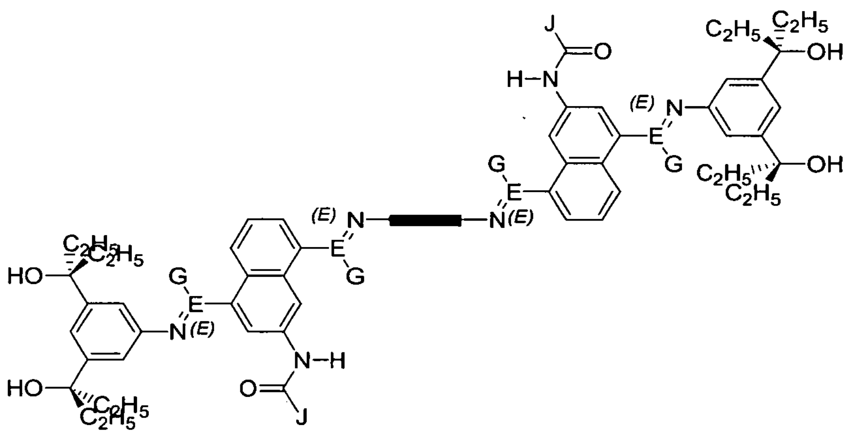
fects) and/or steric effects. The functional effect is to tune the band gap ($\Delta E_{HOMO/LUMO}$) of the molecule to get the desired electronic properties of the molecule. The steric effect is to tune the molecular conformation through steric hindrance, inter- or intra-molecular interaction forces (e.g. hydrogen bonding, Coulomb interaction, van der Waals forces) or to provide bi- or multiple-stability of molecular orientations. They may be any one of the following: hydrogen, hetero atoms (e.g., N, O, S, P, B, F, Cl, Br, and I), functional groups with at least one of above-mentioned hetero atoms, hydrocarbons (either saturated or unsaturated) or substituted hydrocarbons.

[0084] Example 2b below is a real molecular example of the stator-rotor-stator configuration mentioned above:



Red Shifted State (Optical State I)

Red Shifted ⇌ Blu Shifted



Blu Shifted State (Optical State II)

Example 2b

[0085] The molecule shown above (Example 2b) has been designed with the internal rotor parallel to the orientation axis of the entire molecule. In this case, the external field is applied perpendicular to the molecular axis - the elec-

trodes are oriented parallel to the long axis of the molecule and can be either perpendicular or parallel to the plane of the above model structures. For example, application of an electric field to the upper molecule shown above where the field lines are perpendicular to the molecular axis and pointing upward will cause the rotor as pictured in that diagram to rotate to approximately 90 degrees and appear edge on, as shown in the lower molecular diagram above, and vice versa. In this case, the rotor as pictured in the lower diagram is not coplanar with the rest of the molecule, so this is the blue-shifted optical state of the molecule, or optical state II, whereas the rotor is coplanar with the rest of the molecule on the upper diagram, so this is the red-shifted optical state of the molecule, or optical state II. In the diagram, the letters E, G, and J indicate sites where different chemical units can be utilized to adjust the geometrical structure of the molecule, and other chemical groups may also be used as the rotor and stators. The letters C, N, H, and O retain their usual meaning. The letters E, G, and J can be any of the following: hydrogen, heteroatoms (e.g., N, O, S, P, etc.), hydrocarbon (either saturated or unsaturated), or substituted hydrocarbon with at least one of the above-mentioned heteroatoms.

[0086] For the molecules of Example 2, the films are grown such that the molecular axis is parallel to the plane of the electrodes. This may involve films that are multiple monolayers thick. The molecules form solid-state or liquid crystals in which the large stator groups are locked into position by intermolecular interactions or direct bonding to a support structure, but the rotor is small enough to move within the lattice of the molecules. This type of structure can be used to build an E-field controlled display or used for other applications as mentioned earlier herein.

[0087] Examples 1 and 2 show two different orientations for switching the molecules. However, the examples given are not to be considered limiting the invention to the specific molecular systems illustrated, but rather merely exemplary of the switching mechanism disclosed and claimed herein.

[0088] The technology disclosed and claimed herein for forming optical switches (micrometer or nanometer) may be used to assemble displays, electronic books, rewriteable media, electrically tunable optical lenses, electrically

controlled tinting of windows and mirrors, optical crossbar switches for routing signals from one of many incoming channels to one of many outgoing channels, and more.

INDUSTRIAL APPLICABILITY

[0089] The field-switchable molecules disclosed herein are expected to find use in optical devices constructed from micro-scale and even nano-scale components as well as a variety of visual displays.